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# Study of Charmonium Production in Asymmetric Nuclear Collisions by the PHENIX Experiment at RHIC

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The measurement of quarkonia production in relativistic heavy ion collisions provides a powerful tool for studying the properties of the hot and dense matter created in these collisions. To be really useful, however, such measurements must cover a wide range of quarkonia states and colliding species. The PHENIX experiment at RHIC has successfully measured  $J/\psi$ ,  $\psi'$ ,  $\chi_c$  and Upsilon production in different colliding systems at various energies. In this talk I will present recent results from the PHENIX collaboration on charmonium production in d+Au, Cu+Au and U+U collisions at 200 GeV/c.

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# 1 Introduction

Dissociation of quarkonia by color screening in deconfined matter is predicted to be different for different states. Loosely bound states will melt first, and successive suppression of individual states can provide an effective thermometer of the QGP. However, there are many competing processes in nucleus-nucleus collisions: cold nuclear matter effects, color screening, initial state effects, regeneration, feed-down, and so on. Thus, in order to have a clear picture of what happens during relativistic nucleus-nucleus collisions, we need measurements for different energies, colliding species, and quarkonium states. In this respect, asymmetric nucleus-nucleus collisions can be very useful in understanding the importance of different processes contributing to quarkonia production.

## 2 d+Au collisions

The PHENIX experiment has measured  $J/\psi$  production in p+p and d+Au collisions at 200GeV. at forward, backward, and central rapidities [4]. Fig. 1(top left) shows the  $J/\psi$  invariant yields in p+p and d+Au collisions as a function of rapidity, integrated over centrality (0%100%). The error bars (boxes) represent point-to-point uncorrelated (correlated) uncertainties.

The cold nuclear matter effects are quantified by calculating the nuclear modification factor  $R_{dAu}$ , which is defined as the ratio of  $J/\psi$  yield in d+Au collisions to  $J/\psi$  yield in p+p collisions, corrected for the number of binary collisions  $N_{coll}$ .  $N_{coll}$  is derived using a Glauber calculation (see [8] for details).

As expected, nuclear modification factor  $R_{dAu}$  exhibits rapidity asymmetry in d+Au collisions, as is shown in Fig. 1(bottom left). Forward (deuteron going) rapidity shows more suppression than central and backward (Au going) rapidity.

This difference can have many possible explanations, including nuclear breakup and gluon shadowing. A model [6] which uses EPS09 nPDF and breakup cross-section  $\sigma_{br} = 4mb$  shows reasonable agreement with the data. Predictions of this model are shown in Fig. 1 by red curves. A second class of calculations incorporates gluon saturation effects at small-x [7], and is shown in Fig. 1 by green lines. This model fits the data well at forward rapidity, but fails to reproduce them at backward rapidity.

However, if one looks at centrality dependence of  $R_{dAu}$  the picture becomes less unambiguous. Fig. 1(right) shows rapidity dependence of  $R_{dAu}$  for peripheral (top) and central (middle) d+Au collisions, as well as their ratio  $R_{CP}$  (bottom). For peripheral collisions, the  $R_{dAu}$  ratio shows a mild suppression, roughly independent of rapidity, within the systematic uncertainties of approximately 15%. For central collisions  $R_{dAu}$  indicates a much larger suppression for  $J/\psi$  at forward rapidity. As one can see, the model which uses EPS09 nPDF and breakup cross-section  $\sigma_{br} = 4mb$  [6],

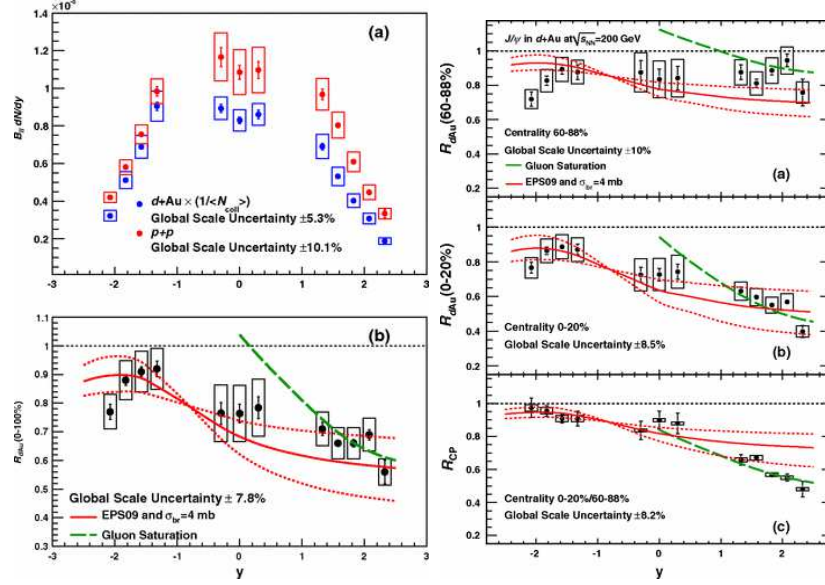


Figure 1: Rapidity dependence of  $J/\psi$  yield in p+p and d+Au collisions (top left), and of  $R_{dAu}$  (bottom left). Rapidity dependence of  $R_{dAu}$  for different centralities (right).

fails to describe the  $R_{CP}$  measurement at forward rapidity. No parameter choice of the EPS09 nPDF set and of  $\sigma_{br}$  is able to describe the rapidity and centrality dependence of the data. Gluon saturation model [7] describes centrality dependence well at forward rapidity, but fails at other rapidities.

Fig. 2 shows transverse momentum dependence of  $R_{dAu}$  for different rapidities. As one can see, at all rapidities,  $R_{dAu}$  rises up to  $5\text{GeV}/c$ . A model which includes shadowing +  $\sigma_{br}$ , shown by red dashed curves, does not match the trend. The model by Kopeliovich et al. [5], which includes Cronin effect and  $\sigma_{br}$  qualitatively matches the shape of observed dependence. Largest disagreement with theories is observed at backward rapidity.

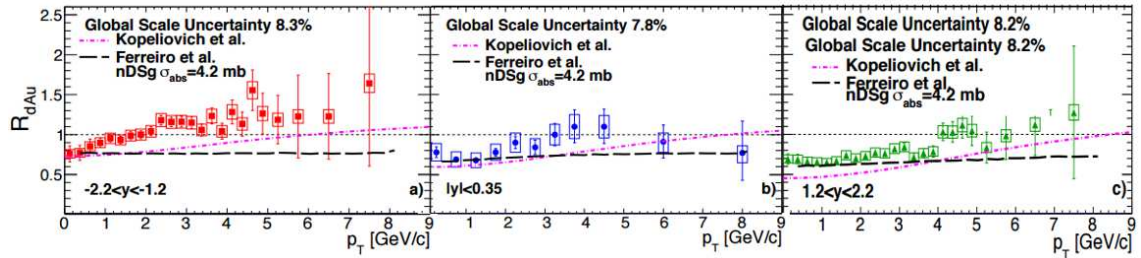


Figure 2: Transverse momentum dependence of  $R_{dAu}$  for three different rapidity ranges.

Fig. 3 shows  $R_{dAu}$  for  $\psi'$  [3]. Unexpectedly,  $\psi'$  is 3 times more suppressed in most central collisions than  $J/\psi$ , and has very different trend with  $N_{coll}$  compared to  $J/\psi$ . Reference [9] presents a model that explains the lower energy E866/NuSea and NA50 relative  $\psi'/J/\psi$  suppression results using an expanding color neutral  $c\bar{c}$  pair. As the  $c\bar{c}$  expands, it has an increased nuclear absorption owing to its larger physical size. Once the time spent by the  $c\bar{c}$  pair traversing the nucleus ( $\tau$ ) becomes larger than the  $J/\psi$  formation time, the  $\psi'$  will see a larger nuclear absorption owing to its larger size. This idea is tested at RHIC energies by calculating the average proper time spent in the nucleus by the quarkonia (or  $c\bar{c}$  precursor).

Fig. 4 shows nuclear crossing time in d+Au for different collision energies. Universal trend with  $dN_{ch}/d\eta$  for several systems, up to 200 GeV is observed. The solid curve in Fig. 4 is the calculation by Arleo et al. [9], which is consistent with the trends observed by E866/NuSea and NA50. However, the PHENIX data show very different  $\tau$  dependence.

The values of  $\tau$  for the PHENIX data are similar to the  $c\bar{c}$  formation and color neutralization time of  $\sim 0.05 fm/c$ , and well below the  $J/\psi$  formation time of  $\sim 0.15 fm/c$  [9]. Therefore the model cannot explain the strong differential suppression of the  $\psi'$  in the PHENIX data.

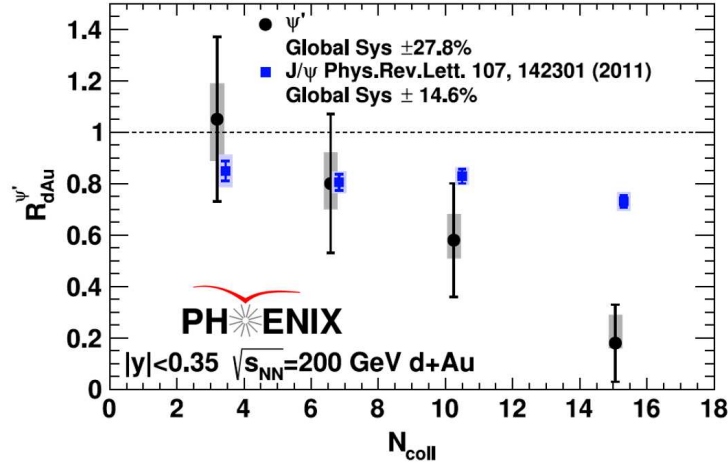


Figure 3:  $R_{dAu}$  for  $\psi'$  and  $J/\psi$  as a function of centrality. Note that the  $J/\psi$   $R_{dAu}$  plotted here is not corrected for  $\chi_c$  and  $\psi'$  feed-down, and the  $N_{coll}$  values are shifted slightly to aid in clarity.

### 3 Cu+Au collisions

Fig. 5 shows  $J/\psi$   $R_{AA}$  vs. centrality for Cu+Au collisions [10] as open black circles (backward rapidity) and solid black circles (forward rapidity).  $R_{AA}$  for Au+Au

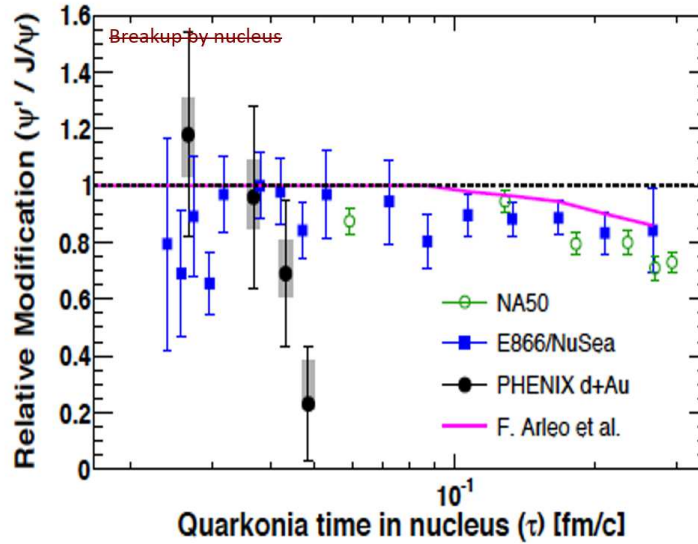


Figure 4: Relative modification  $\psi' / J/\psi$  as a function of quarkonia time in nucleus. The curve is a calculation by Arleo et al. [9] discussed in the text.

collisions is shown on the same plot for comparison as orange points. Observed suppression is somewhat smaller in peripheral Cu+Au collisions, compared to Au+Au collisions, but becomes the same with increasing centrality. Higher suppression is observed in the region of lower particle density (forward rapidity), similar to d+Au collisions. Debye screening would go in the other direction.

Fig. 6 shows a ratio of  $R_{AA}$  for Cu-going and Au-going directions. This ratio has the advantage of reduced systematic uncertainties. Observed ratio decreases with centrality. The 20%–30% difference in suppression between forward and backward rapidity  $R_{AA}$  evident in Fig. 6 could be due to hot matter effects, CNM effects, or a combination of both. Also shown in this figure as solid line is a model [11] which estimates the contribution from cold nuclear matter (shadowing). The grey band in this figure represents the extreme nPDF parameter sets for the model.

As can be seen from Fig. 6 the difference between forward (Cu-going) and backward (Au-going)  $J/\psi$  modification is found to be comparable in magnitude and of the same sign as the expected difference from shadowing effects.

## 4 U+U collisions

Collisions of deformed uranium nuclei produce a wide variation in energy density within the same colliding system. MC studies show [1] a possibility of selecting experimentally tip-tip collisions by selecting high multiplicity, but low flow events.

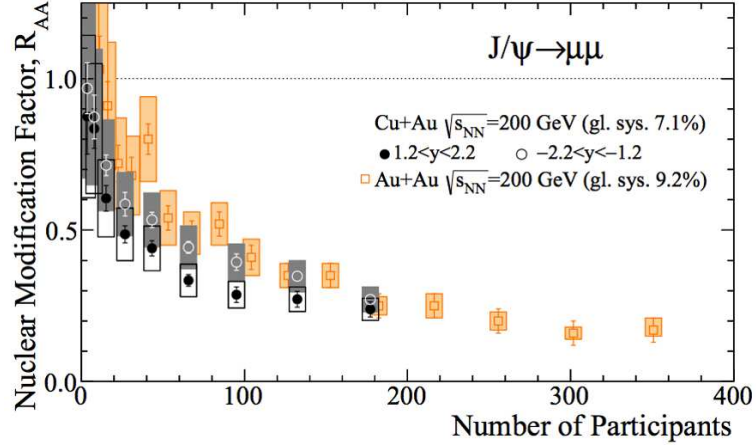


Figure 5:  $R_{AA}$  vs. centrality for Cu+Au and Au+Au collisions.

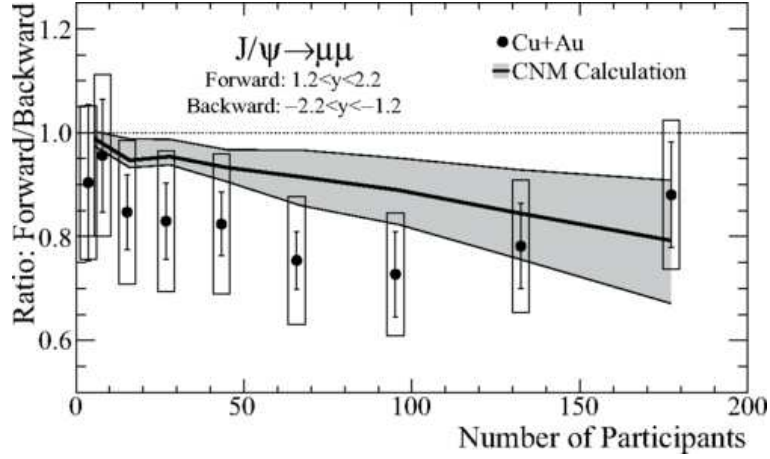


Figure 6:  $R_{AA}$  ratio for Cu-going/Au-going directions in Cu+Au collisions.

In tip-tip collisions  $T/T_C$  could reach above 2 [2], at which temperature  $\Upsilon(1S)$  could dissociate.

The PHENIX collaboration recently measured  $J/\psi$  production in U+U collisions at 200 GeV. Fig. 7 shows preliminary results of  $J/\psi$   $R_{AA}$  as a function of centrality for U+U collisions (black circles) compared to Au+Au and Cu+Cu collisions. Qualitatively similar  $J/\psi$  suppression is observed from Cu+Cu to U+U collisions. Somewhat weaker suppression in most central U+U collisions may indicate higher role of coalescence processes in uranium-uranium collisions.

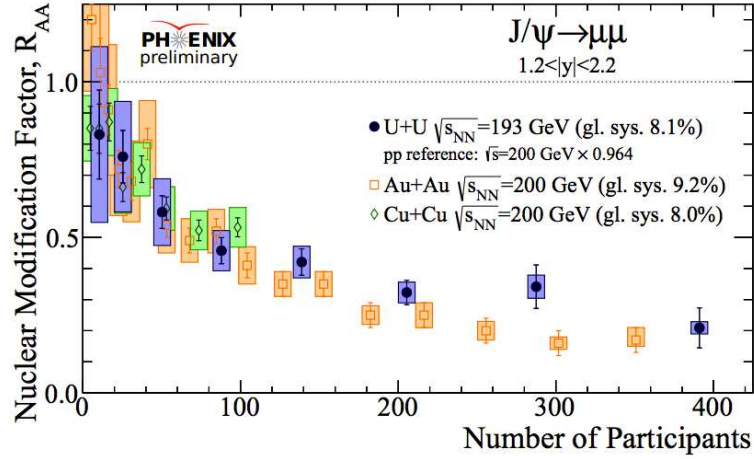


Figure 7:  $R_{AA}$  vs. centrality for U+U collisions (black circles) compared to Au+Au and Cu+Cu collisions (open symbols).

## 5 Conclsions

In d+Au collisions  $J/\psi$  nuclear modification factors at forward rapidity as a function of centrality cannot be reconciled with a picture of cold nuclear matter effects (nPDFs and  $\sigma_{br}$ ) when an exponential or linear dependence on the nuclear thickness is employed.

In Cu+Au collision, the Cu going side is more suppressed than Au going side, consistent with CNM effects (shadowing).

The magnitude and trend of  $\psi(2s)$  suppression in nuclear collisions is quite different from that of  $J/\psi$ . Nuclear crossing time does not explain the data.

$J/\psi$   $R_{AA}$  is qualitatively consistent between different colliding systems, from Cu+Cu to U+U.  $\sim 25\%$  differences could be due to expected variations in the CNM and QGP effects.

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